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# Mid-Wave ZGP OPOs Pumped by a Cr:ZnSe Laser

**Wayne S. Pelouch, Gregory J. Wagner and Timothy J. Carrig**

*Coherent Technologies, Inc., 655 Aspen Ridge Drive, Lafayette, CO 80026*

*Phone: (303) 604-2000, Fax: (303) 604-2500, e-mail: [waynep@ctilidar.com](mailto:waynep@ctilidar.com)*

**William J. Scharpf**

*Naval Air Warfare Center Aircraft Division, 48110 Shaw Rd. Unit 5, Patuxent River, MD 20670-1906*

**Abstract:** We describe Type I and Type II ZnGeP<sub>2</sub> OPOs operating in the 4-6  $\mu\text{m}$  region. The OPOs are pumped by a gain-switched Cr<sup>2+</sup>:ZnSe laser.

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Wayne S. Pelouch, Gregory J. Wagner and Timothy J. Carrig

Coherent Technologies, Inc., 655 Aspen Ridge Drive, Lafayette, CO 80026

Phone: (303) 604-2000, Fax: (303) 604-2500, e-mail: [waynep@ctilidar.com](mailto:waynep@ctilidar.com)

William J. Scharpf

Naval Air Warfare Center Aircraft Division, 48110 Shaw Rd. Unit 5, Patuxent River, MD 20670-1906

Broadly tunable mid-infrared laser sources are of interest for a variety of applications including differential absorption lidar, differential scattering lidar, multi-spectral detection and imaging, optical communications in poor visibility conditions and spectroscopy. A variety of laser and nonlinear optical devices have been demonstrated that access this spectral region. To date, however, direct solid-state lasers that operate at wavelengths longer than 4  $\mu\text{m}$  have not been practical for field deployment under harsh conditions. Typical problems include low electrical efficiency, low output power, operation at cryogenic temperatures and use of hygroscopic gain media. Consequently, nonlinear optical devices, in particular optical parametric oscillators, have been developed as a more robust means of generating moderate to high power mid-wave infrared (MWIR) output.

Typical MWIR OPO materials include  $\text{ZnGeP}_2$  (ZGP),  $\text{AgGaSe}_2$ ,  $\text{CdSe}$  and  $\text{LiNbO}_3$  (in both bulk and periodically poled forms). Of these materials, ZGP has the highest thermal conductivity (by an order of magnitude), the highest damage threshold, and the largest nonlinear figure-of-merit (by a factor of six). A significant disadvantage of ZGP, however, is that it is not transparent at wavelengths shorter than  $\sim 2 \mu\text{m}$  and suffers absorption at wavelengths shorter than  $\sim 2.1 \mu\text{m}$ . This eliminates the possibility of pumping ZGP with many well-developed solid-state lasers.

Moderate power (10 W) and high efficiency ( $>55\%$  optical conversion) MWIR ZGP OPOs have been demonstrated using 2.09  $\mu\text{m}$  Ho:YAG lasers as pump sources [1], [2]. These devices are critically phase-matched OPOs that output at fixed MWIR wavelengths. Improvements to this technology may be possible using longer wavelength (to minimize absorption in the ZGP crystals) and tunable (to permit pump tuning) lasers as pump sources. Towards this end we report, to the best of our knowledge, the first use of tunable  $\text{Cr}^{2+}:\text{ZnSe}$  lasers [3] to pump ZGP OPOs. Advantages of this system include: (1) both the laser and OPO operate well at room temperature, (2) both the laser and OPO can operate with very high efficiency, (3) both materials have very high thermal conductivity and (4) non-critically phase-matched (NCPM) pump-tuned OPOs can be built.

In this effort both Type I and Type II OPOs were built and characterized. In both cases the OPO pump source was a gain-switched  $\text{Cr}^{2+}:\text{ZnSe}$  laser that output approximately 0.35 mJ pulses at a 1000 Hz pulse repetition frequency. The  $\text{Cr}^{2+}:\text{ZnSe}$  laser was tunable over the range of 2200-2700 nm. The  $\text{Cr}^{2+}:\text{ZnSe}$  laser was pumped by a Q-switched Tm:YALO laser operating at 1940 nm. The Tm:YALO laser output pulse energies of 0.75 mJ. The Tm:YALO laser output Gaussian shaped pulses with a full-width-half-maximum of 198 nsec while the Cr:ZnSe laser output a pulse whose shaped was governed by relaxation oscillations [4]. Figure 1 illustrates the experimental setup.

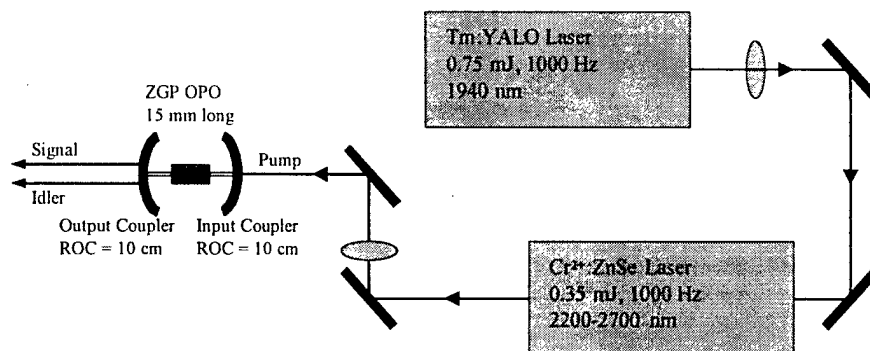


Figure 1. Typical experimental arrangement used to build both Type I and Type II OPOs.

In Type I configuration, the OPO was operated in both degenerate and non-degenerate modes. The ZGP crystal was 15 mm long and cut with  $\theta = 49.5^\circ$  and  $\phi = 0^\circ$ . The  $\text{Cr}^{2+}:\text{ZnSe}$  laser pump beam was focused to an approximate  $135\ \mu\text{m}$  radius spot within the ZGP crystal. The OPO cavity consisted of two 10 cm radius of curvature mirrors. The overall cavity length was approximately 2.3 cm. When pumped at  $2.35\ \mu\text{m}$  the OPO operated near degeneracy and output approximately 82 mW at  $4.7\ \mu\text{m}$ . Figure 2 shows OPO output power as a function of pump power incident on the input coupler.

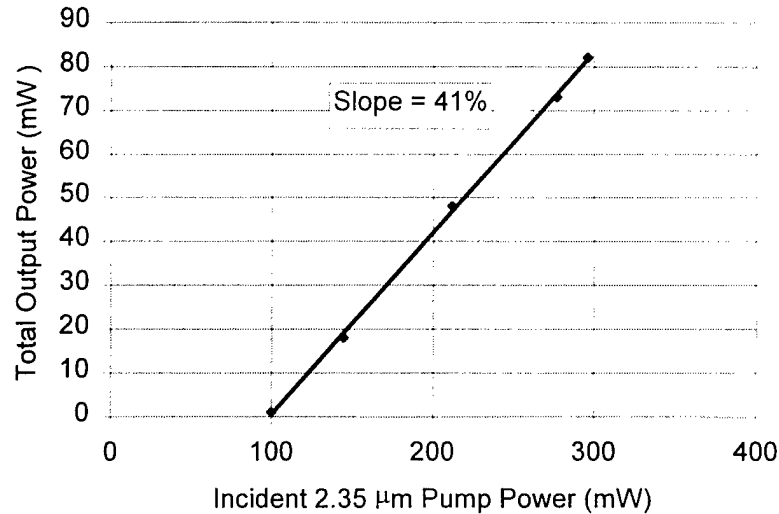


Figure 2. Total OPO output power as a function of incident pump power for a Type I ZGP OPO operated at degeneracy. The OPO was pumped at  $2.35\ \mu\text{m}$  and output at  $4.7\ \mu\text{m}$ .

In the degenerate case shown above, the signal and idler were collinear. The OPO displayed an incident power threshold of approximately 0.1 mJ and a slope efficiency of 41%. As expected from an OPO operating near degeneracy, the output spectrum was quite broad, with a total (signal plus idler) linewidth of up to 1200 nm (the pump laser was also multi-longitudinal mode). The OPO mirror coatings were not optimized for conversion efficiency and higher slope efficiencies were observed away from degeneracy.

We also characterized a NCPM Type II OPO. The ZGP crystal was 15 mm long ( $\theta = 90^\circ$  and  $\phi = 45^\circ$ ). The cavity configuration was identical to that used for the Type I OPO. Figure 3 shows OPO output when the pump laser was tuned to  $2.55\ \mu\text{m}$ .

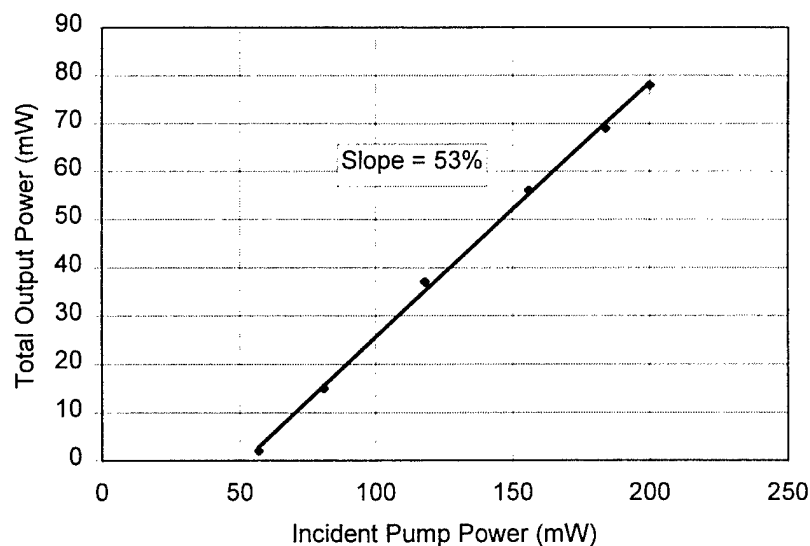


Figure 3. Total OPO output power as a function of incident pump power for a Type II ZGP OPO pumped at  $2.55\ \mu\text{m}$ . The OPO output at  $4.7\ \mu\text{m}$  and  $5.6\ \mu\text{m}$ .

The OPO output a total power of up to 100 mW and displayed an incident power threshold of 0.05 mJ and a slope efficiency of 53%. With the 2.55  $\mu\text{m}$  pump wavelength, the OPO output signal and idler beams at 4.7 and 5.6  $\mu\text{m}$ . The OPO beams had linewidths on the order of 15 nm. This linewidth was primarily governed by the linewidth of the multi-mode pump beam. The signal and idler were collinear. Figure 4 shows an emission spectrum of the NCPM Type II OPO output.

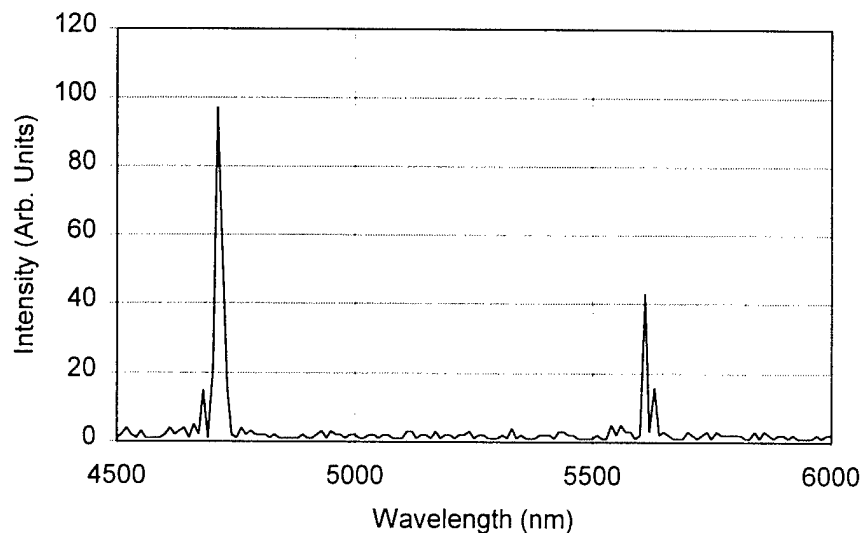


Figure 4. Output spectrum of the Type II NCPM ZGP OPO when pumped at 2.55  $\mu\text{m}$ .

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